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Addressing the technical and market challenges to high wind power integration in Ireland

A.M. Foley [a,b,c], B.P. Ó Gallachóir [b,c,*], E.J. McKeogh [b,c], D. Milborrow [d], P.G. Leahy [b,c]

[a] School of Mechanical & Aerospace Engineering, Queen's University Belfast, Ashby Building, Stranmillis Road, Belfast, BT9 5AH, United Kingdom
[b] Department of Civil & Environmental Engineering, School of Engineering, University College Cork, College Road, Cork, Ireland
[c] Environmental Research Institute, University College Cork, Lee Road, Cork, Ireland
[d] Energy Consultant, Lewes, East Sussex, BN7 1LR, United Kingdom

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ABSTRACT

Over the last decade there has been a rapid global increase in wind power stimulated by energy and climate policies. However, as wind power is inherently variable and stochastic over a range of time scales, additional system balancing is required to ensure system reliability and stability. This paper reviews the technical, policy and market challenges to achieving ambitious wind power penetration targets in Ireland's All-Island Grid and examines a number of measures proposed to address these challenges. Current government policy in Ireland is to address these challenges with additional grid reinforcement, interconnection and open-cycle gas plant. More recently smart grid combined with demand side management and electric vehicles have also been presented as options to mitigate the variability of wind power. In addition, the transmission system operators have developed wind farm specific grid codes requiring improved turbine controls and wind power forecasting techniques.

Contents

* Corresponding author at: University College Cork, Department of Civil and Environmental Engineering, College Road, Cork, Ireland. Tel.: +35 321 4903037; fax: +35 321 4276648.
E-mail address: b.ogallachoir@ucc.ie (B.P. Ó Gallachóir).

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1. Introduction

The European Union (EU) has set a number of policy objectives to achieve a sustainable energy future for Europe through measures to tackle climate change, to ensure energy security and to enhance competitiveness [1–3]. One result of this has been the rapid growth of wind power within the EU and plans for further accelerated deployment. Most EU Member States have set ambitious targets for increased renewable energy penetration within electricity markets in particular and are assessing the associated technical, policy and market challenges on an on-going basis [4–6]. This paper focuses on the challenges for one region, Ireland, which is an interesting case study in terms of the current level of wind power penetration, the issues being addressed and the ambition in the period to 2020. The electricity market and policy barriers are also discussed and some variability mitigation measures are examined.

The Republic of Ireland and Northern Ireland are two separate jurisdictions but share a synchronous power system, the All Island Grid (AIG) and since November 2007, a single electricity market (SEM). Useful measures to compare synchronous power systems in relation to the technical challenges posed by accommodating wind energy are wind power penetration on an energy basis or alternatively installed capacity penetration (i.e., the installed wind generating capacity as a proportion of the total installed capacity). In terms of scale, Great Britain's(GB) power system is more than nine times larger than the AIG. The Nordel power system in Scandinavia is nearly 30% larger than GB's. The UCTE[1] system is significantly larger than Nordel, stretching from the Adriatic to the Atlantic and from the Baltic to the Mediterranean, and covers the bulk of the remainder of continental Europe. By the end of 2005, wind power penetration on the AIG was greater than either UCTE or Nordel[2] [7]. Given that Ireland's installed wind capacity has more than doubled since 2005, this points to a greater urgency for solutions to be found for Ireland than elsewhere in Europe.

In 2005 the Ministers responsible for energy policy in the Republic of Ireland and Northern Ireland jointly issued a preliminary consultation paper called the '2020 Vision' for renewable energy [8]. In the '2020 Vision' wind power was identified as key to achieving Ireland's renewable energy targets. However, at the launch of '2020 Vision' there were queries regarding the actual feasible levels of wind power that could be integrated and the need for further analysis was agreed by both governments and regulators. Subsequently, in January 2008 an AIG study was published, which examines the impacts of renewable energy on the AIG [9]. The findings of this study provided the confidence needed to put in place the subsequent ambitious targets. The Republic of Ireland has a target of generating 40% electricity from renewable energy sources (RES) by 2020 [10]. Northern Ireland initially had a renewable target of 12% electricity production from indigenous sources by 2012 [11]. However, this was increased to 40% power from renewable sources, mostly from offshore wind power, by 2020 [12]. There are a number of key technical challenges associated with large scale wind power integration, linked firstly to the stochastic nature of the wind and secondly to the fact that wind generation does not use directly connected synchronous machines. The degree of wind power variability, uncertainty and instantaneous penetration determines the additional system balancing impacts on power system security, reliability and stability and the associated costs [13].

[1] UCTE referred to the Union for the Co-ordination of Transmission of Electricity.

[2] In July 2009, both UTCE and Nordel were wound down and became part of the European Network of Transmission System Operators for Electricity (ENTSO-E), which includes Association of the Transmission System Operators of Ireland, Baltic Transmission System Operators, European Transmission System Operators and UK Transmission System Operators Association, as well as Nordel and UTCE.

2. Power system challenges

The AIG system has an existing installed dispatchable capacity of 9742 MW, of which approximately 5842 MW is gas fired [14,15]. Currently there is an installed wind power capacity of circa 1533 MW. Fig. 1 shows the growth in installed wind power capacity and the forecasted for 2020.

Foley et al. describe the state-of-the-art in wind power forecasting and prediction methods [16]. The most important application of wind power forecasting is to reduce the need for balancing energy and reserve power, which results in the additional grid integration costs associated with wind integration [17]. In Ackermann et al. the experience of increasing levels of wind power in the AIG are described and up to then there have been no incidents where wind power directly or indirectly caused operational problems for the AIG [18]. In April and March of 2010 there were at least three curtailment events when instantaneous wind power penetrations in excess of 40% of load occurred during periods of low demand [19]. There is a rule of thumb that wind power levels in excess of 50% are curtailed [20]. In 2012 a wind farm was put hold due to new curtailment rules in the AIG [21]. Therefore, further challenges can be expected as the current installed capacity is set to increase by more than 70% by 2020.

Gardner et al. concluded that there is no technical limit to wind power levels in the AIG, but rather transmission reinforcement, other technical system constraints and operating costs are the determining factors [22]. Current policy has resulted in plans for substantial grid reinforcement, interconnection and additional gas peaking plant to integrate increased levels of wind power [23–25]. In addition, the Transmission System Operators[3] (TSO) in Ireland have also developed specific grid codes for wind generation specifying the technological requirements that need to be met and requiring robust wind power prediction to integrate the current levels of wind power [26,27]. A 'Demand Side Vision for 2020' consultation document issued jointly by the regulators[4] has also recognised the potential of demand side management (DSM) to support Irelands renewable energy targets [28].

2.1. Long term planning

In traditional long term planning a number of reliability indices are used to plan the generation portfolio mix. These indices are capacity- or power- based and take into account random, partial and complete forced outages and the variations in load demand [29]. However, when planning a power system with wind power, capacity credit is widely used to determine the amount of installed thermal plant that can be replaced by wind power [30]. Amelin demonstrated that there is a correlation between capacity credit and loss of load probability (LOLP[5]) [31].

[3] ESB National Grid (ESBNG), formerly part of the Electricity Supply Board (ESB) signed the agreement, but since 1st July 2006, EirGridplc assumed the role of TSO in the Republic of Ireland and the System Operator for Northern Ireland (SONI), formerly part of Northern Ireland Electricity (NIE), but since 2008 SONI has been a wholly owned independent part of EirGrid.

[4] Commission for Energy Regulation (CER) and the Northern Ireland Authority for Utility Regulation (NIAUR).

[5] Loss of Load Probability (LOLP) is the instantaneous probability that the load exceeds the available generation; the year-round integrated value is the Loss of Load Expectation (LOLE) i.e., the expected number of hours over a year that there will be a supply shortage.

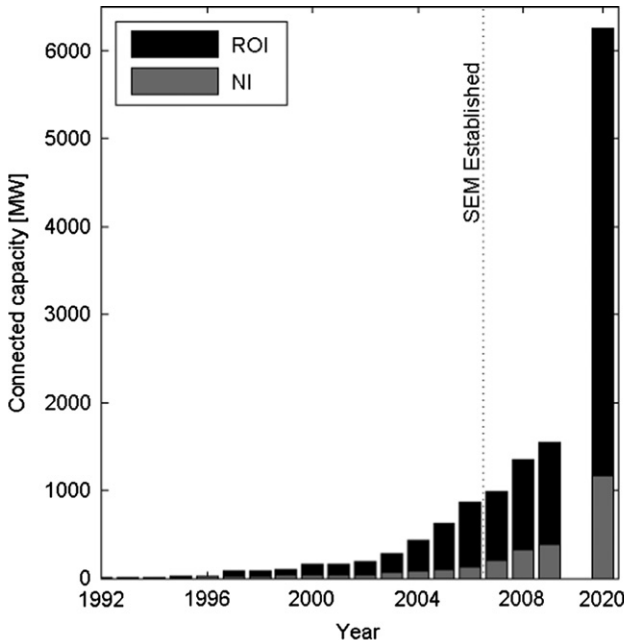

Fig. 1. Total installed wind generation capacity in the AIG from 1992 to 2009 and targets for 2020.

In conventional long term generation expansion planning a least cost model such as the Wien Automatic System Planning[6] (WASP) tool is usually employed, whereby a number of scenarios or portfolios are examined [32,33]. In the initial stage of the AIG study a more simple least-cost portfolio algorithm was applied in order to agree on a number of possible future portfolios [34]. Five portfolios were selected and dispatch modelling was undertaken using WILMAR[7] [35]. The AIG study also questioned the availability of the additional transmission network infrastructure by 2020 and identified that immediate policy changes were needed if the renewable energy targets were to be achieved [36]. The pace of transmission grid delivery has so far been slower than anticipated due to permitting and licensing delays.

In the AIG study energy storage was not fully tasked, in fact it limited to Turlough Hill, and DSM was not included, although the latter was subsequently assessed [37]. This perhaps clarifies the need for the additional fast response gas peaking plant in the AIG study as wind penetrations increased. In addition, while the AIG study did include transmission network reinforcement costs in the analysis, it did not consider additional distribution network reinforcement costs [38]. The costs indicated in the study are far lower than those subsequently estimated by the TSO to support RES at the transmission level. The TSO in Ireland have large transmission grid reinforcement projects of £1billion and €4billion planned, respectively, to support wind power and grid development [23,24]. Value for money in terms of grid infrastructural investment should be an important technical, policy and market decision in terms of achieving Ireland's renewable energy targets by 2020. Linking long term planning tools with short term high temporal resolution models as discussed in Deane et al. should be considered as part of long term planning to improve future predictions under different scenarios [39].

2.2. Short and medium term technical challenges

The variability of wind power affects system operational costs and relates directly to reserve requirements and the dispatch of plant. ESBNG estimated that increasing wind power penetration in the Republic of Ireland from 0% to 11.7% would result in an increase in total generation costs of €196 million and that the largest change was in the operation of mid-merit order plant with 15 to 100 additional start-up's per year [40]. Doherty and O'Malley determined that very little fast acting reserve is needed in the AIG even at high wind power penetrations [41]. More recently, Ortega-Vazquez and Kirschen developed a new technique to calculate spinning reserve[8] that minimizes the total cost of operating the system [42]. Ortega-Vazquez and Kirschen [42] note that the methodology proposed by Doherty and O'Malley [41] actually results in suboptimal solutions because a single level of reliability is set for all periods of the optimization horizon. This is because the cost and benefit of the reserve provision changes from period to period depending on the demand, wind production and units committed. In the AIG study, heavy reliance is made on replacement reserve from open cycle gas turbines (OCGT) peaking plant but the availability of so many OCGT is not actually considered [34]. Furthermore, some base load thermal units have a large number of start-ups per annum and it appears that there is no lower limit on the number of dispatchable plant in operation in order to maintain system reliability. This results in an underestimation of plant and system operation costs [32]. In an analysis of short term wind turbine availability by Conroy et al. it was shown that while the technical non-availability at an operational wind farm as a percentage of time is 3%, the percentage of energy lost during downtimes is actually 11% [43].

Large scale wind integration can also affect power system inertia and frequency because wind generation does not use directly connected synchronous machines and different wind turbines can cause different system effects [44]. Dudurych et al. presents the types of wind turbines in operation in the SEM and suggests that appropriate energy storage technologies and fast-starting thermal plant can support wind power integration [45]. System inertia[9] is particularly important in smaller, more isolated power systems such as the AIG, with a relatively limited rotating inertia [46]. Feeley et al. consider compressed air energy storage (CAES) and pumped hydro energy storage (PHES)as a system resource and assess the impact of wind and storage on the AIG system without any market influences [47]. In the study the use of mid-merit plant increased as storage increased. Tuohy et al. also suggest that at increased wind power levels system reserve requirements in the AIG change [48]. In Tuohy and O'Malley it was demonstrated that PHES resulted in reduced wind curtailment events using a stochastic unit commitment model at high wind penetration levels of between 34% to 68% [49]. Troy et al. established that at high wind power penetration levels, the cycling of base load plant also increases in the AIG [50]. The same research showed that at high levels of wind penetration interconnection and storage improved system operation.

[6] Wien Automatic System Planner (WASP) was created by the Tennessee Valley Authority and Oakridge National Laboratory with maintenance by the International Atomic Energy Agency (IAEA) to specifically carry out long term generation expansion planning.

[7] Wind Power Integration in Liberalised Electricity Markets (WILMAR) was developed at the Risø National Laboratory with a number of other partners as part of a European Commission fifth framework project to study the integration of wind power in the very short to medium term for Denmark, Finland, Germany, Norway and Sweden with up to one year hydro resource planning.

[8] Spinning reserve (SR) is unused capacity, which can be activated on decision of the system operator and is provided by devices, which are synchronized to the network and able to affect the active power.

[9] Inertia of a power system is related to the rate of change of frequency directly after a disturbance.

The AIG study also considered the ability of the transmission network to absorb only firm[10] wind power, using three seasonal operating snapshots in order to identify grid reinforcement requirements [38]. In light of the large amount of wind power anticipated, further dynamic studies were identified as needed. The Facilitation of Renewables (FOR) studies (2010) investigated dynamic (transient) stability impacts of large amounts of instantaneous wind penetration in the AIG [51]. A key finding is that frequency response and the dynamic stability are impacted at high instantaneous penetrations of wind power. It also found that voltage and reactive response would require additional management. Instantaneous power from wind and import will have to be limited to between 60% and 80% of load and export in 2020 MW and 3775 MW of wind power decreases power system control reserve by a factor of almost two [52,53]. The FOR studies recommend that the existing standard protection relays on the distribution network, the ride through capability of thermal generators, the primary reserve requirements of thermal generators, the Grid Codes and operation standards all need to be reviewed to meet the 40% renewable target. Other than a small study of flywheel at five locations, energy storage and DSM did not form part of the FOR studies.

2.3. Impacts on gas resource planning

A further challenge that has not received adequate attention in studies or the literature is the impact of increasing variable intermittent wind power on the gas network. Increasing levels of varying wind power will have the effect of changing the usage profile of gas at thermal generators as wind ramps-up and -down on the system. However, it should be noted that the absolute level of wind fluctuations will not always be reflected in the variations seen by a TSO, as demand fluctuations may attenuate – or enhance – the wind fluctuations [54]. A reduction in gas consumption has the potential to result in higher gas transportation rates as gas network infrastructure costs are relatively fixed [32]. Ireland imports approximately 94% of its natural gas supply from GB via the Moffat entry point and the remainder comes from the Kinsale gas field [55]. The Joint Gas Capacity Statement (2010) also acknowledges that the low levels of wind power and extreme periods of cold weather such as that experienced during the winter of 2009 place significant demands on the gas systems in Ireland and that there will continue to be a substantial demand on gas generation to back-up wind power. Gas storage projects are identified and the commencement of operations at Corrib gas field are discussed, particularly with regard to reverse natural gas flows from the west coast to the east coast, as currently gas flows from the east to west. Upgrades, reinforcements and potential changes in regulatory, transport and shipper arrangements to facilitate potential natural gas exports to the GB are also mentioned in the Joint Capacity Statement (2010). However, the mechanisms or gas system changes required to support the variations in wind power are not evaluated.

Qadrdan et al. notes that wind integration studies in GB have also neglected the impacts on the gas network and that large wind power penetration will cause increased flows and compressor power consumption on the gas network, whereas during low wind periods line pack depletion can limit the ability of the gas network to supply gas thermal generators, especially combined cycle gas turbines (CCGT) [56]. CCGT may have to operate at a reduced capacity with other options employed to meet the shortfall. Qadrdan et al. [56] suggest that gas interconnectors and liquid natural gas (LNG) will play a major role in GB in 2020. It was demonstrated that gas suppliers, shippers and generators will be exposed to hourly balancing costs, which will affect gas prices and procurement. Qadrdan et al. [56] also suggest that in order to mitigate the impacts of wind power variability on the gas infrastructure, gas generators should be dual fired, using distillate oil and liquefied petroleum gas, again requiring storage.

2.4. Comparison with international experience

In one of the earliest studies carried out to assess the economic and operational implications of wind power integration in GB by Farmer et al. it was found that low levels of wind power penetration maintained the existing level of security of supply and that there was no operational necessity for storage up to a wind output capacity of at least 20% of system peak demand [57]. However, the economic case for storage did exist. According to Farmer et al. [57] when there was sufficient wind power penetration to displace low marginal cost generation and as the dispersion of wind farms increased. So too did the operational worth of storage increase in servicing shortfalls and generation uncertainties against the scheduling of large steam units. In Gross et al. [58] also known as the ‘UKERC Intermittency Report’ over 80 wind integration studies were examined. All these studies show that variable generation does contribute to system reliability through a positive capacity credit, and that capacity credit expressed as a percentage of intermittent output declines as the variable generation penetration level rises [58].

Holttinen et al. examines a number of wind power integration studies from Europe and the USA and highlights that because different metrics were used to examine wind power impacts and costs with distinct methodologies, timescales and datasets, it is difficult to compare the studies and the result is that a range of balance and reserve costs are identified [59]. However, Holttinen et al. [59] notes that as wind power levels increase in GB and Ireland, integration will be more challenging than in other systems because during critical moments of high wind and low load, due to the lower level of interconnection relative to the other European systems. One interesting aspect with regard to that statement in Holttinen et al. [59] is that the AIG appears to have the lowest reserve requirement, the lowest balancing costs and an average lower grid reinforcement cost relative to the larger more interconnected power systems. In the same study it was concluded that energy storage did not bring any additional power system value to the AIG. However, in GB wind power integration costs appear to be higher and the value of storage was estimated to be between 252£/kW and 970£/kW based on work carried out by Strbac et al. [60]. Holttinen et al. [59] related this difference between GB and the Ireland studies to the costs benefit approach used in the AIG. In DeCesaro et al. (2010) wind power grid integration studies in the USA are reviewed and it is concluded that considerable changes in traditional grid planning and operations are required to encourage more flexible generation [61].

3. Electricity market challenges

Electricity markets are varied and complex. The nature of electricity means it has to be traded instantaneously because it is difficult to store, unlike other commodities. Thus liquidity[11] in liberalised electricity markets is limited [62]. The Office of Gas

[10] Firm meaning fully dispatchable.

[11] Liquidity can be described as the ability to quickly buy or sell a desired commodity or financial instrument without causing a significant change in its price and without incurring significant transaction costs. A key feature of a liquid market is that it has a large number of buyers and sellers willing to transact at all times.

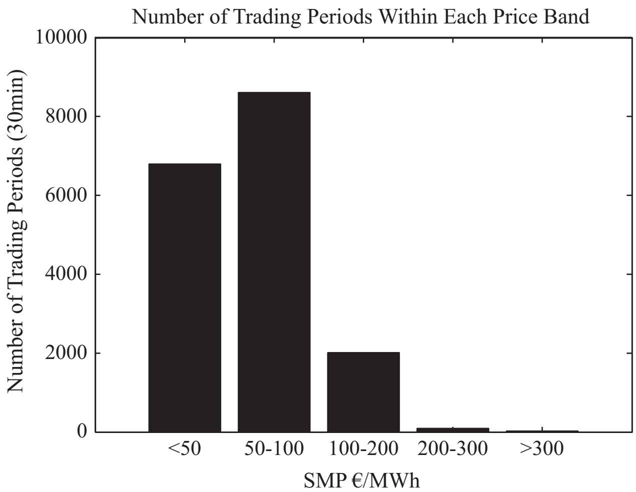

Fig. 2. Occurrence of Settled SMP Bands in the SEM, 2009.

and Electricity Markets (Ofgem) describe liquidity in the GB wholesale electricity market (BETTA[12]) as low, relative to many other European markets [63]. McInerney states that one of the best measures of market integration is price convergence and that retail electricity prices in the SEM zone can be used as a good proxy of market integration, which are constantly higher than GB and the EU [64]. Fig. 2 shows the results of a review of settled SMP data in 2009 and reveals that the SEM has little activity in terms of price spikes. This lack of volatility in the SEM makes arbitrage between the SEM and other markets and within the SEM less opportunistic for pure market traders, peaking plant and energy storage.

3.1. Wind support mechanisms

In general wind power like other RES has been incentivised by a variety of support mechanisms and the burden of balancing costs has ultimately been borne by the consumer in the form of levies, taxes and other charges. In EU Directive 2009/72/EC provision is made for public service obligation (PSO) levies in order that a Member State can impose regulatory requirements on the electricity industry in the general economic interest for '*security of supply, quality and price of supplies, environmental protection, including energy efficiency and climate protection,*' the so-called three pillars [65]. The PSO levy is a mechanism, which enables electricity suppliers to recoup the cost of having to source some electricity from RES. In the SEM wind power is supported via the following:

- the alternative energy requirement (AER) scheme, a competitive tendering process that guaranteed generators 15 year power purchase agreements with the public electricity supplier to the successful bidders. This support scheme was introduced in the Republic of Ireland in 1993 and has supported over 500 MW in the period up to 2007,
- the renewable energy feed-in tariff (REFIT)scheme, was introduced in the Republic of Ireland in 2005 as the successor to the AER support scheme. Renewable generators enter into 15 year power purchase agreements with suppliers at negotiated and fixed prices. REFIT compensates participating retail electricity suppliers via the Public Service Obligation (PSO) levy mechanism, according to the REFIT terms and conditions for the net additional costs attributable to their participation in the scheme and purchase of electricity from the relevant generators in the REFIT scheme and,
- the renewable obligation scheme in place in Northern Ireland where an obligation is placed on electricity suppliers to ensure a proportion of their electricity comes from renewable sources. Compliance is achieved based on Renewable Obligation Certificates (ROC) issued to generators based on their renewable energy production.

In addition to accommodating three different market support systems, the SEM also has endogenous obligations to legacy contracts, which add another layer of complexity to regulatory requirements to meet policy obligations and to satisfy all market participants. There are also exogenous barriers to wind power integration similar to traditional thermal generators, which cannot be readily covered by the internal electricity market and policy decisions. Valentine discusses some of the social, technical, economic and political forces that prevent wind power development [66]. Ó Gallachóir et al. provides a critical review of wind energy policy successes and shortcomings in Ireland [67]. Green suggests that more centralised markets improve co-ordination, dispatch and reduce wind power integration costs [68].

Under the PSO levy, these RES schemes, a number of legacy contracts and indigenous fuel sources are supported. Tuohy et al. shows that supporting a certain type of thermal generation using an indigenous fuel, in this instant peat, although beneficial in terms of energy security, it is not beneficial economically or environmentally [69]. A similar argument for regarding wind power subsidisation can be made. From an environmental perspective wind power is positive, but from a security of energy supply and economic perspective the status of the current set-up is questionable, especially as wind power levels increase. At the current levels of wind power, the PSO levy has not been an issue, but as wind penetration levels increase so too will the PSO levy. Furthermore, when electricity demand and wholesale market prices are low the result is a sizeable PSO levy passed onto customers. The economic slowdown in the Republic of Ireland has seen a sizeable increase in the PSO for 2010/11 [70].

Furthermore, REFIT payments are variable and linked to increases in the consumer price index (CPI). Therefore, no reductions can be made for inflation, meaning that REFIT contracts are a hedge against inflation [32]. REFIT reference prices are lower than most feed-in tariffs in other countries, where they are fixed or are linked to market prices. As installed wind power increases, REFIT may ultimately prove expensive to customers. ROC payments are adjusted in line with the retail price index (RPI), meaning that payments reflect the state of the economy. In light of the current economic climate and the findings of the FOR studies (2010), perhaps REFIT, the PSO levy mechanism and the general SEM structure should be re-examined as Ireland's renewable energy targets appear to require some major redesigns. In Huber et al. [17] different support mechanisms in the Irish context are assessed [71]. An analysis of the expected costs and value of the Irish REFIT support scheme for wind generation by Doherty and O'Malley suggests that a Fixed Price scheme provides similar or greater incentive to the wind sector at half the cost to the end electricity consumer [72]. Balance this with the energy efficiency action plans set by both governments, whereby ambitious CO_2 reduction targets have been identified [73,74]. Thus a key challenge is to meet Ireland's energy needs and targets in a cost efficient manner, so that all energy market participants make a profit without burdening society with exorbitant taxes and charges.

[12] BETTA refers to the British Electricity Trading and Transmission Agreements.

3.2. Generation portfolio with in the SEM

Generation expansion planning has become far more complicated since the introduction of market liberalization where the price of electricity is determined in a wholesale market. De Vries provides a detailed discussion of the various electricity market designs, which incentivise electricity generation [75]. According to Finon and Pignon market liberalisation has fundamentally altered the approach to reliability and security of supply as policy and regulatory authorities must now plan adequate generation capacity [76]. Credibility is described by Lyons et al. as the ability of the state to pre-commit so that the rules of the game will not change once irreversible investments are in place and an increase in the number of power companies can also be seen to add credibility, competition and volatility to the market [77]. Uncertainty in market credibility results in under investment in the market [78]. In order to add credibility to the SEM in November 2006, CER and the ESB, the former vertically integrated utility responsible for generation, transmission and distribution, agreed a package of measures to reduce ESB share of the power generation market, known as the ESB 'Asset Strategy Agreement' [79]. The purpose of the agreement was to foster more competition in the electricity market by reducing ESB share to approximately 40% by 2020, streamline ESB, improve market function and benefit electricity customers. ESB has a current market share of 45.6% [80]. Privatisation of Northern Ireland Electricity (NIE) began in 1992, whereby the power stations were separated into individual companies. Then in 1998, the regulated and non-regulated parts of NIE were decoupled and set-up in a new holding company called Viridian Group Plc., which subsequently was purchased by Arcapita and then sold to ESB in 2010.

In Malaguzzi Valeri and Tol the age profile of Ireland's generation portfolio is described as old and with one of the lowest availability operation rates in Europe [81]. The generation portfolio in GB is also quite old. This is also compounded by Directive 2001/80/EC, referred to as the Large Combustion Plant Directive [82]. Between 1999 and 2007, when the Republic of Ireland experienced a period of strong economic growth and increased electrical demand, this was seen as a serious security of supply issue and replacement thermal generators were planned. However, due to the long permitting delays and the current financial markets, a large number of these thermal plants have now been put on hold, especially those planned by new market entrants. In addition unknown future regulatory changes and uncertainty in future electricity demand, irrespective of the Ireland's renewable energy targets, has also made it difficult to leverage finance. The market appears to lack creditability. Lyons et al. [77] believe that the cross-border dimension in the SEM adds credibility to the market as the market is agreed between two sets of governments and regulators. However, this can also be a weakness as it can slow down well needed change in the market, without mutual agreement of all parties and a full and proper consultative period.

All the scenarios analysed in the AIG study [9] assume an increasing demand in electricity up to 2020. However, this was before the reduction in electricity demand due to the recession [83]. The net impacts of increasing variable wind power, lowering electricity demand and idle or partially loaded thermal plant, which are subject to cycling and ramping, has not been fully modelled in the SEM. Puga notes that fast ramping of CCGT and other steam plant in the USA as wind power penetration levels increase will require proper pricing of ancillary services or other forms of compensation so that thermal plant remain viable [84]. Lyons et al. [77] expected that the number of OCGTs to increase *'because the demand for generation capacity net of wind power should become more volatile as the share of wind generation rises'*. Generators in the SEM bid into the market at zero to guarantee dispatch and under the current SEM design the system marginal price[13](SMP) will decrease as wind power levels increase [64]. The current market structure going forward does not appear to encourage competition or new entrants amongst thermal generators because of the current economic outlook and financial conditions, as well as the market mechanisms, whereas for renewable and other generators, who entered the market prior to the present financial turmoil, the *status quo* of guaranteed payment is more preferable. As highlighted by Lyons et al. [77], *'to achieve the best long-run outcome, the SEM's regulators need to ensure that the capacity mechanism accommodates a set of strategies by all players (incumbents, entrants, government) that will lead to the highest possible societal welfare'*.

In CER and NIAUR (2009) the impact of high levels of wind penetration in the SEM in 2020 is examined and draws the following conclusions:

1. SMP prices are significantly lower with increased wind power levels, irrespective of fuel and carbon prices,
2. the economic benefits of increased wind power are sensitive to fuel and carbon prices,
3. new generator incentives appear uncertain as they are portfolio dependent,
4. a mixed portfolio has a better impact on CO_2 emissions, rather than gas base load plant and wind alone [85].

An important issue with these conclusions is that the final retail electricity price charged to the end-user should assist in determining the real wholesale market impacts. Also the impact of the PSO levy should be included in calculating the final retail price. Furthermore, the latest AIG indications are that gas base load plant and variable wind power will have the majority share of the 2020 generation portfolio. Therefore, it is suggested that a re-run of this study should be undertaken.

3.3. Interconnection withinthe SEM

The AIG is interconnected via the Moyle[14] 500 MW high voltage direct current (HVDC) link to NGUK, which is currently limited to 80 MW exports, 450 MW of import in winter and 400 MW in summer due to contractual and technical issues. There is also EirGrid's 500 MW HVDC East West interconnector (EWIC), which runs from County Dublin to North Wales, which is expected to be fully operational by the end of 2012. Studies, which have examined the impacts of interconnection between the NGUK and AIG include the Doherty et al. [41], AIG study [9], .Foley et al., EirGrid, MalaguzziValeri and Cox [86–90] and the Irish Academy of Engineering [32]. In the AIG study [9], the construction of a second interconnector (i.e., EWIC) between the AIG and the United Kingdom National Grid (UKNG) is a precondition for the feasibility of all generation portfolios. In Foley et al. the wind correlations across the British Isles were studied in terms of increased wind power penetration and real technical benefits of the EWIC [86]. EirGrid [88] examines the economic feasibility of interconnection between the AIG and GB or France in terms of production cost savings and capacity benefits. The key findings of this study are that there is a strong economic case for the EWIC by 2020 and more so in 2025, particularly in the high renewables scenario and that an Ireland-France interconnector also appears economically attractive, especially in terms of capacity and

[13] The System Marginal Price (SMP) equals the capacity payment plus constraint payment.

[14] The Moyle Interconnector is owned and operated by Moyle Interconnector Ltd.

reductions in production costs. SMP prices are expected to decrease because wholesale prices and gas prices in GB are lower than in Ireland. However, electricity market issues in the EU designated France, UK and Ireland (FUI) trading zone are seen as significant. Malaguzzi Valeri [89] presents a study of the welfare and competition effects of electricity interconnection between Ireland and the GB and concluded that in order to establish a single GB Ireland market using the Residual Supply Index (RSI) developed by Sheffrin [91] that about 1700 MW of interconnection would be required [91]. However, Malaguzzi Valeri [89] does not consider that GB may be able to balance its spatially variable wind resource better by regional dispersion of wind farms within its own area rather than by interconnection with Ireland. Cox [90] presents the results of a study on the effects of variability on the Irish and GB electricity markets. Some of the findings are similar to those in the study undertaken by Foley et al. [86].

EirGrid has stated that EWIC is necessary for security of supply, to encourage competition in the electricity sector, to increase penetration of renewable energy and allow exports and imports of surplus electricity [92]. However, since 2005 there has been a deficit of fossil fuel generation in GB year on year and from a review of NGUK data on the Anglo-French Interconnector (IFA) power flows are predominantly from France to England, due to market issues, even though during the same period a large generation plant margin exists in the UK. A study of trades across the Moyle interconnector in August 2009 does indicate a lack of hedging ability in the SEM and to a lesser extent the lack of hedging in the BETTA is the primary reason for little traffic. McInerney highlights that because the Moyle Interconnector links two trading regions within a single nation, it is not subject to the same EU rules on congestion management charges and that trade only occurs in 1 to 3 year contracts and monthly standard contracts [64]. Attempts have been made to increase traffic on the Moyle interconnector with the introduction of a non-standard contract auction. Trade on the IFA is daily, monthly and annually because it is subject to EU congestion management charges. Larkin [93] provides a critique of the SEM Regional Integration consultation paper in his pre-consultation response and notes that trade on the IFA, by vertically integrated players, is mostly to balance their portfolio, rather than to trade under arbitrage [93]. Larkin [93] says that the Moyle interconnector is constrained by similar issues even though it links two separate trading jurisdictions' and concludes that major decisions are required in the SEM to improve trade.

Ofgem [63] also describes that because the SEM does not have a day-ahead market, potential traders on the Moyle interconnector have no indication of the SMP when settling their position in the neighbouring market. Ofgem [63] consider this a major impediment to price coupling of the SEM to other markets. Also because the SEM does not allow trading after gate closure, there can be unused interconnector capacity available at gate closure in the market. This is important for the proposed EWIC, in terms of compliance with the EU rules on congestion management. In addition to the Moyle interconnector constraints already discussed, capacity payment in the SEM is split over three periods, which results in uncertainty and makes arbitrage even more difficult [64]. It could be argued that this also has the potential to limit market participation and opportunities for new entrants, portfolio diversification, DSM and electricity storage.

Trading on the EWIC has been modelled in the SEM on the basis that power flows are predominantly west from the NGUK to the AIG [88]. It is only in the generation portfolio with the highest wind penetration that the AIG registers small amounts of exports. Interconnector economics and benefits have been widely investigated and these studies have shown that interconnectors yield undoubted economic and technical benefits, but these benefits are maximised when there is only one single system operator responsible for both unit commitment and dispatch in the geographically connected areas [94,95]. In the NGUK and AIG, there are in effect five separate transmission and distribution owners (Scottish Power, Scottish & Southern, NG Plc., ESB and NIE) and three TSOs(NGUK, EirGrid and SONI). In March 2010, ESB purchased the Northern Ireland transmission and distribution business from the Arcapia-owned Viridian Group, which means that the number of transmission and distribution owners is now reduced to four [96].

4. Addressing the challenges

Interconnection and the various proposals for a European super grid are seen as measures to mitigate the variability of wind power using geographical dispersion. Europe's TSO already have plans for improved interconnections, most of which are likely to benefit wind energy [97]. However, as discussed by Gross and Heptonstall geographical smoothing of variable power sources is not the only reason for interconnection [98]. Interconnection, and by the same logic, the proposed European super grid also enable electricity market participants to share the impact of variability across a larger collection of conventional and energy storage resources, as well as different demand profiles, which should ultimately reduce the cost of balancing. Decker et al. [99] have recently summarised most of the European super grid proposals that are currently being discussed. Some cater, in the longer term, for up to 100 GW of offshore wind [99]. Hurley et al. [100] provided data that illustrated the smoothing effects and suggests that the capacity credit of this widely distributed wind might be higher than the values calculated from individual national studies. Similarly, their analysis of power swings also suggests that there would be a lower uncertainty, probably leading to lower additional balancing costs [100]. Either way, it is difficult to correctly value the contribution from wind energy [101].

Interconnection of the AIG and NGUK is suggested as attractive for the SEM because the east west exchange of electricity mirrors the frequently observed eastbound path of depressions from the North Atlantic, with associated high wind speeds. Cox also observed that the larger the geographic area of installed wind power, the more steady and less intermittent the wind power generation because of the decreasing correlation in wind speeds at larger distances [90]. However, the flexibility believed possible in Ireland may not become available by interconnection to the NGUK alone, due to the anticipated growth of wind power and large base load in the GB system as examined in the literature review. The results of the meteorological analysis by Foley et al. indicate that the NGUK may be able to balance its spatially variable wind resource better by regional dispersion of wind farms within its own jurisdiction rather than by interconnection with Ireland [86]. In fact AIG technical constraints may be amplified in the much larger NGUK system because of the future high levels of wind power planned and nuclear base load in the NGUK generation portfolio. Furthermore, the NGUK grid is stronger on the north-south axis than the east–west axis and the EWIC, like the Moyle interconnector, will be linked to a weak part of the NGUK on the west coast [92]. This was not considered byCox [90]. These issues need careful analysis and examination, particularly in terms of the AIG placing reliance on importing electricity from GB to support variability issues.

If the errors in wind power forecasting are reduced then electricity markets can trade with more certainty. Contract errors as a function of time in electricity markets can be as high as 39% for a forecasting lead time of 4 h [102]. Offshore wind farms pose more of a challenge in terms of accurate wind power forecasting

and prediction because the environment is typically flat and smooth with very few obstacles so changes in wind speed and thermal effects are felt more acutely than on land as weather fronts pass over the wind farm [103,104]. A review of published data has gleaned very little knowledge of methods in use for offshore wind power prediction [16,104]. This is another area, which will be a considerable challenge in the future, especially as off shore wind power levels increase.

Wind power production in most of northern Europe is stronger in winter than in summer [105]. However, this complements the peak electricity demand as the load in winter is higher than in summer. Notwithstanding there are extreme periods of low wind speeds in winter when demand is at its highest [106]. This can also be linked to the research of Qadrdan et al. [56] where variability in wind power show increased gas prices, procurement costs and storage costs, beyond 2020 in GB. Extreme highs and lows may result in even higher costs across other sectors such as the industrial, commercial and residential sectors. Wind power has a strong seasonal dimension. During the summer, the fall in wind power production is greater than the reduction in demand, which means than the summer can be particularly challenging [107]. Thus the impacts of the affects of high and low wind power levels on the gas supplies in the AIG and SEM should also be considered. Wind shows less diurnal than seasonal consistency with load, so as the total installed capacity of wind power increases wind power prediction as well as power and gas system planning and operations will become even more challenging. Wind forecasting should be carried out across the British Isles as a joint exercise so that wind integration can be more effective.

4.1. Mitigation measures

In Foley et al.electrical energy storage and smart grid technologies were reviewed in-depth to integrate RES, particularly wind power [108]. DSM, electric vehicles and PHES are deemed suitable in terms of technical development for wind power integration in the AIG [105,108,109]. An analysis by Milborrow identified ten possible mitigation measures for variable renewables [110].

There are many types of DSM measures, although the boundaries are not sharp. In GB during 2005/6, users, rather than generators provided about one-third of the 'standing reserve and 'frequency response' balancing service requirements of NGUK [111]. Dynamic demand is a passive system that relies on sensors in equipment used by consumers to modulate demands. If all domestic refrigerators, for example, included a frequency-sensitive device that inhibited its operation when the frequency fell below (say) 49.8 Hz and switched the fridge on (provided it was not already too cold) at, say 50.2 Hz, then this could substitute for between 728 MW and 1174 MW of frequency response plant [112]. Smart meters give electricity consumers access to information about the price of their electricity on a continuous basis. The most common perception of such meters at present is to provide information to consumers, rather than intervene to restrict demand on a selective basis. Smart meters for domestic consumers, as presently envisaged, are a source of usage information and it is up to the consumer to respond or not. Time of use tariffs have been in existence for many years in the industrial and commercial sectors, and, in simplified form, in the domestic sector. Tariffs aim to discourage use at peak demand times that normally coincide with peak prices and so iron out, to some extent, demand fluctuations. If that enables the quantity of rarely used (and expensive) peaking plant to be reduced, then both costs and emissions are also reduced. The most sophisticated development of time of use pricing responds continuously to changes in market prices. Whether or not consumers can react to high or low prices depends on the type of electrical equipment they are using. All these concepts act to improve the efficiency of the electricity system as a whole. Any benefits to wind power integration would come through reductions in the costs of balancing services. One possible downside from DSM is that a reduction in the uncertainties in the supply/demand balance might mean that the uncertainties in wind power production would become more significant, thus increasing additional balancing costs. The other issue with DSM is the actual cost of the infrastructure and the charge to the customer to actually support DSM, even though in the long run customer benefits.

In Fitzgerald et al. the potential to transform electric water heating, a passive load, into an intelligent responsive agent capable of reducing electricity consumption as part of a demand response program, to reduce peak demand and provide some balancing load to assist in the integration of variable wind power in the SEM is examined [109]. This is a form of DSM. The results of the model indicated that only when wind power penetration is over 30% can electric water heating provide more than 175 MW of load modulation. The model shows that intelligent dynamic load control electric water heating for wind power integration has limited viability. Notwithstanding, this is particularly relevant in Ireland, which has a small grid system and a large planned growth in installed wind capacity. Another similar type of technology to electric water heating is electric space heating. At present, electric space heating and electric water heating is significantly more expensive than gas or oil-fired heating. A move towards more electric space heating and electric water heating in the AIG, could potentially provide the TSO with a large source of inexpensive DSM. Such a shift in emphasis might be the result of high fossil fuel prices, carbon taxing, government incentives, or both. The signals that would enable TSO to influence demand levels could be transmitted through 'smart controls' or one of the other technologies. The concept is actively being considered in Denmark [113].

Electric vehicles have been suggested as the solution to wind curtailment, grid congestion and variability problems associated with excess wind electricity during a peak or off peak period. In the EU each Member State is mandated to ensure that 10% of transport energy (excluding aviation and marine transport) comes from renewable sources by 2020 [114]. The Irish Government intends to achieve this target with a number of policies including ensuring that 10% of all vehicles in the transport fleet are powered by electricity by 2020 [115]. However, EirGrid noted that from the grid viewpoint there are questions with regard to the time when EV charging takes place, the number of EVs charging and the interaction between the EV technology and the grid [116]. Uncontrolled EV charging may result in power losses, transformer and line overloads and a reduction in power quality (e.g., voltage, unbalance, frequency and harmonics), which may cause inconvenience to customers, especially at the distribution level [117]. Foley et al. examines the implication in terms of infrastructure requirement, energy demands and GHG emissions in the SEM [118–120]. The challenges to the electrification of the private passenger car sector include uncertainty in predicting the actual size of the load and time of load due to technology development, driver behaviour, even actual EV car sales and uncertainty in estimating the amount of displaced tailpipe GHG emissions to the thermal generators. Then there are other barriers such as the actual availability and price of EVs, the roll-out and capital costs of charging infrastructure including smart metering and billing and EV standardisation to ensure public take-up and acceptance. The impacts of EV charging in the SEM and AIG requires further investigation to determine capital infrastructure costs and to ensure that current EV policy is effective.

Internationally PHES has been recognised as a technology that can integrate RES with over 23.4 GW either in planning or

well advanced in terms of construction [121,122]. Some countries have exhausted their PHES sites. However, this is not the case in the UK and Ireland. Scottish Southern Energy's has advanced proposals for two PHES in the Great Glen in Scotland, with an installed capacity of 300 MW and 600 MW each [123]. There is also a highly conceptual PHES series of schemes, referred to as the 'Spirit of Ireland' proposal, which supply 100% energy independence for Ireland using wind power and PHES [124]. Then there are some private PHES proposals, as well as a CAES site in Country Antrim [125–129]. The current SEM design, competition from cheaper gas thermal generators, relatively low carbon prices, the existing price of natural gas and the lack of volatility in the SMP does not appear to support the financial development of PHES to integrate wind power [130,131]. This is a considerable impediment to PHES development in the AIG. However, in the future this may change if gas market prices and volumes fluctuate and carbon taxes are fully introduced making gas thermal plant less competitive resulting in increases in the price-elasticity of the SMP. This would allow arbitrage and thus PHES and CAES.

Finally, there is the possibility of coupling wind with tidal and wave. Dalton and Ó Gallachóir study developing a wave energy policy and Dalton et al. presents the findings of an analysis of a 10 year installation program for wave energy in Ireland [132,133]. In terms of ocean energy development, offshore wind power is far more advanced than wave power and an advanced offshore wind power coupling wave to wind as an integrator has potential. Coupling shows some but not very significant system improvements [134]. The links is supported by the findings of the Irish-Scottish Links on Energy Study (ISLES), which assessed the feasibility of creating an offshore interconnected transmission network and subsea electricity grid to capture wind, wave and tidal energy off the coast of western Scotland and in the Irish Sea/North Channel area [135].

5. Discussion and conclusion

A common theme in all the wind power integration studies is that as the levels of wind power penetration increase there are many power system impacts. As highlighted by Bazilian et al. the interaction of wind power and an electricity system is multi-faceted and there are considerable challenges presented by large amounts of wind power [136]. Additional balancing and back-up can directly and indirectly increase cycling and gaseous emissions at thermal plant. The cost of the balancing and back-up is linked to the flexibility of the existing power system.

Current indications are that progress towards the target of generating 40% electricity from RES in the AIG will be more rapid than in other markets. It is also evident that wind power forecasting has a major role to play in wind power optimisation, to estimate the size and scale of system reinforcements and upgrades, the amount of balancing, reserves and storage. An unexpected result of this study was the impact of wind power intermittency on the gas network and the potential need for additional gas storage, which is another form of energy storage. A comparable study to that carried out by Qadrdan et al. [56] is suggested in the AIG.

Wind power integration studies indicate that a diversified portfolio appears to have the least risk. Diversification in the AIG study [9] considered solely additional thermal generation. Diversification can include additional thermal generation, increased RES and energy storage and DSM and increased market competition. Unlike the earlier AIG study [9] the cost implications of the recommendations relating to short term integration of instantaneous increases in wind power levels have not been estimated in the recent FOR studies (2010). It would be prudent to carry out a more in depth long term financial analysis, as all of the studies to date have not considered the costs fully as a large number of technical constraints, additional infrastructure, market impacts and changes to existing regulatory mechanisms have been identified in this paper. This should not halt or prevent current activities, because perfect forecasting and planning is stochastic and dependent on many external uncontrollable variables.

The various variability mitigations proposed also have issues. The main challenges to DSM, electrical energy storage, electric vehicle roll-out and smart grid technology in the AIG and SEM are the capital investment costs, the unknowns associated with planning, operation and management and the existing SEM structure. In the current market system there is no impetus on the market players to develop energy conservation and efficiency measures, without strong policy initiatives. A key difficulty with DSM is financing and fair cost distribution amongst consumers. The ultimate quandary in the AIG and SEM is to allow the current *status quo* of the market players to continue and invest in heavy grid reinforcement and interconnection, even though it is highly probably that price of fossil fuels will increase and carbon pricing may place additional burden on the market participants. Maintaining the current SEM structure will also be difficult in the current economic climate. Then there is the role of the retail electricity market and modernisation of the distribution system using smart grid technologies. The retail electricity market and information communication technology (ICT) opportunities at the distribution level have not been discussed in all the studies to date. The sale of mobile phone licences in Ireland in the early 1990s led to an upturn in the economy. The sale of retail electricity licenses could led to a new ICT-energy related economic growth, bring much needed funds to the exchequer, change consumer behaviour, support a better more efficiency power system, enable grid enhancements and lead to a true carbon market. These are all policy decisions.

The interaction of the SEM with the much larger BETTA market needs serious evaluation. As Conlon concludes, given the coupling of the SEM and larger BETTA, the survival of the SEM as a gross mandatory pool is doubtful. Potentially the SEM may move towards a BETTA-like bilateral market arrangement [137]. Eitherway, the issues examined in the study need to be expedited and resolved. Harmony in policy, electricity system planning, ICT-energy technology and wholesale and retail market design is very important. A FUI market model should also be undertaken in order to maximise all electricity resources not just RES, which examines all the future power system development scenarios.

Finally, in this paper the technical, policy and market challenges to integrate wind power in the AIG are addressed and the limitations of previous studies are discussed in light of recent developments. There are many uncertainty issues surrounding interconnection as the ultimate solution to high levels of wind power. However, it is clear that portfolio diversification in terms of DSM, energy storage and the payment and policy mechanisms, which drive renewable energy and thermal generation merit inclusion in any further studies. There is no perfect solution, because even the variability mitigation measures have challenges. The ultimate question for policy makers is can Ireland deliver a low carbon society with the existing SEM structure.

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